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13. ABSTRACT *(Maximum 200 words)*

In microwave and millimeter-wave circuit applications the issue of RF packaging is becoming an important subject to address due to the lack of appropriate packaging configurations for high-frequency circuit design. Several years back, experts in the field of device and component development began to realize that packaging of such components was progressing at much slower rate than the devices themselves. As a result, many problems observed in device and component performance at these frequencies are being attributed, after diagnostic testing, to the package in which they are housed. Typical problems associated with circuit packages, especially above X-band, include resonances due to the large physical geometry surrounding these circuits, cross-talk caused by parasitic radiation from neighboring circuits, and unwanted excitations that result in power leakage in the form of substrate modes. Many of these issues can be addressed by integrating the package with the circuit monolithically, by **on-wafer packaging**, which implies that the package is fabricated as part of the circuitry and is designed to meet performance specifications. With state of the art advances in semiconductor processing techniques, silicon micromachining offers what conventional means have not been able to provide; packages which conform to the circuit geometry, provide on-wafer electromagnetic and environmental protection, require much less space and provide superior mechanical, thermal and electrical performance.

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Technical Report

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February 1996

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(1) F. Drayton and L. P. B. Katehi, "Development of Self-Packaged High-Frequency Circuits Using Micromachining," IEEE Transactions on Microwave Theory and Techniques, Vol. 43, No. 9, pp. 2073-2080, September. 1995.

2) Krumpholz and L. P. B. Katehi, "MRTD: New Time Domain Schemes Based on Multiresolution Analysis," IEEE Transactions on Microwave Theory and Techniques, Vol. 44, No. 4, pp. 555-571, April 1996.

3) F. Drayton, T. M. Weller and L. P. B. Katehi, "Development of Miniaturized Circuits for High-Frequency Applications using Micromachining Techniques," invited paper, International Journal of Microcircuits and Electronic Packaging, Vol. 18, NO. 3, Third Quarter, 1995.

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5) L.P.B. Katehi, "Si Micromachining for High-Frequency Applications," Invited Paper, submitted for publication in the IEEE Informer.

6) R. F. Drayton and L. P. B. Katehi, "Micromachined Conformal Packages for Microwave and Millimeter-Wave Applications," Proceedings of the 1995 IEEE Symposium on Microwave Theory and Techniques, Orlando, FL, pp. 1387-1390, Vol. 3, May 1995.

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11) M. Krumpholz, E. Tentzeris, R. Robertson and L.P.B. Katehi, "Time Domain Analysis of Microwave Structures by MRTD," Proceedings of the 1996 ACES Symposium, Monterey, CA, pp. 1303-1309, Vol. II, March 1996.

12) M.Krumpholz and L. P. B. Katehi, "A New FDTD Scheme Based on Orthonormal Wavelet Expansions," Proceedings of the 1995 Progress in Electromagnetics Symposium (PIERS), Seattle, WA, July 1995.

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8. SCIENTIFIC PERSONNEL SUPPORTED BY THIS PROJECT AND DEGREES AWARDED DURING THIS REPORTING PERIOD:

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BRIEF OUTLINE OF RESEARCH FINDINGS

During the reporting period our effort concentrated in two specific applications: (a) The development of a micropackage for mm-wave circuits covering frequencies from 20 GHz to 94 GHz (b) The development of a versatile full-wave technique for the efficient characterization of very complex geometries. The progress of our study in each one of these projects is discussed briefly below:

(a) Micromachined Conformal Packages for Millimeter Wave Applications

In microwave and millimeter-wave circuit applications the issue of RF packaging is becoming an important subject to address due to the lack of appropriate packaging configurations for high-frequency circuit design. Several years back, experts in the field of device and component development began to realize that packaging of such components was progressing at much slower rate than the devices themselves. As a result, many problems observed in device and component performance at these frequencies are being attributed, after diagnostic testing, to the package in which they are housed. Typical problems associated with circuit packages, especially above X-band, include resonances due to the large physical geometry surrounding these circuits, cross-talk caused by parasitic radiation from neighboring circuits, and unwanted excitations that result in power leakage in the form of substrate modes. Many of these issues can be addressed by integrat-

ing the package with the circuit monolithically, by **on-wafer packaging**, which implies that the package is fabricated as part of the circuitry and is designed to meet performance specifications. With state of the art advances in semiconductor processing techniques, silicon micromachining offers what conventional means have not been able to provide; packages which conform to the circuit geometry, provide on-wafer electromagnetic and environmental protection, require much less space and provide superior mechanical, thermal and electrical performance.

In the past few years, the use of Si micromachining in microwave and millimeter-wave circuit applications has been extensively explored at the University of Michigan, leading to many innovations. Among these have been the capability to develop self-packaged circuit components which have demonstrated superior electrical performance when compared to conventionally developed components. It is this latter effort that led to the first demonstration of a monolithic conformal package that follows the layout of the circuit and provides on-wafer electromagnetic shielding. One very important characteristic of this packaging approach is that it allows for the development of three-dimensional monolithic circuits and interconnect networks.

The concept of on-wafer, conformal packaging has been applied to both circuits as well as antenna feed networks. The use of such a package on the feeding lines of two microstrip patch antennas reduced the cross talk from -20dB to -60 dB and improved matching by as 80% in bandwidth, as shown on the same figure. for frequencies as high as 40 GHz. Similar reduction is expected at W band. **The on-wafer packaging work received the third prize in the student paper competition by the IEEE Microwave Theory and Techniques Society during the 1995 International MTT-S Symposium in Orlando, FL.** The work on Silicon Micromachining for the development of monolithic Antenna Circuits has found very broad interest in industry during the past year. Specifically, **Hughes Aircraft** is planing on the development of a new 94GHz monopulse radar system using RF micromachining concepts developed at Michigan. Furthermore, **M/A COM** is interested in combining their Glass Process with the conformal packaging concepts developed at Michigan for wafer integration schemes. **ARPA** is also interested in advancing the work on high-frequency micromachining. This implies that there will be a serious effort by the industry to implement some of the ideas developed at Michigan in their future systems. In addition to the above, a small company has shown interest in commercializing the Ka-band micromachined filters we have developed. These filters have exhibited excellent performance with less than 0.8 dB conversion loss up to 40 GHz.

(b) Use of Multiresolution Analysis in Frequency and Time Domain High-Frequency Techniques

During the past few years, our effort on high-frequency modeling has focused on the use of the recently developed multiresolution analysis. Studies performed at Michigan have indicated that multiresolution analysis provides a superior mathematical framework for the development of numerical techniques which are appropriate for high-frequency applications. The use of multiresolution analysis has been proven so effective due to its capability to approximate an unknown function by its weighted average and differential simultaneously, in contrast to conventional numerical techniques which use only weighted averages. The weighted averages are calculated by the use of scaling functions, known as basis functions in conventional modeling, while the

weighted differential are calculated by the use of the wavelet functions. Less information about the weighted averages of a function is needed when adequate information about the weighted differentials is provided. Furthermore, the weighted differentials only attain a non-negligible value when the function exhibits a local variation. As a result, the multiresolution analysis retains only critical but important information about the function, thus, requiring less computational memory and time to specify the unknown function. This is a revolutionary approach for computational electromagnetics and has already demonstrated its potential through the application problems we have treated.

This past year multiresolution analysis was applied to both frequency and time domain and the results were astonishing. In the frequency domain, multiresolution analysis with intervalic wavelets was applied for the first time to characterize microstrip patch antennas. Due to the use of weighted differentials, the application multiresolution analysis transforms the integral equation into a matrix equation in a similar way as the conventional method of moments. However, the resulting square matrices are highly sparse in contrast to the conventional method of moments which provides highly dense matrices. Sparsities of the order of 92-99% have been observed and solutions of the order of a fraction of a second per frequency point for a microstrip patch antenna have been recorded. In the time domain, multiresolution analysis has been applied for the first time to yield new time domain schemes (MRTD). The use of this techniques have resulted in excellent accuracy (error<0.1%) for discretization approaching the Nyquist Sampling Limit of two points per wavelength. Furthermore, these unambiguously low errors were achieved with two orders of magnitude savings in memory and time. Beyond, however, the demonstrated savings in memory and time, this new technique allows, for the first time, for the development of a time adaptive and a frequency adaptive meshing capability. The demonstration of this capability is presently underway. During this past year, our work on the use of multiresolution analysis in frequency domain was awarded with the **2nd prize in the 1995 International IEEE Microwave Theory and Techniques Symposium, in Orlando, Florida**.